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EVALUATION OF GEOTHERMAL PROSPECTS AND THE OBJECTIVES OF GEOTHERMAL EXPLORATION

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SUMMARY

Some of the basic considerations involved in the evaluation of geothermal prospects are reviewed. The elementary principles of the extraction of heat from geothermal reservoirs are discussed on the basis of an example. It is concluded that in order to sustain power generation in the 100 MW range geothermal reservoirs must have temperatures at or above 200 °C and their volume must be of the order of several hundred cubic kilometers. Other important conditions are discussed. A brief review is given of the technique of geophysical exploration of geothermal prospects.

INTRODUCTION

Natural steam and hot water are available for power generation and heating purposes in many volcanic regions of the world. The first major commercial exploitation of this resource was initiated in Tuscany, Italy, at the beginning of the century. Methods of harnessing and producing natural steam in large quantities for power generation were subsequently developed by the Italians. A total of 400 MW of electric power is being generated now by natural steam in Italy. Domestic and industrial heating by natural heat was initiated in Iceland in 1925, and almost 100,000 people there now live in houses heated in this way. More recently, geothermal power production has been taken up in New Zealand, Iceland, Japan, U.S.A. and the U.S.S.R. Geothermal power plants in New Zealand already have a capacity of about 200 MW, and no doubt a considerable further expansion is possible. Moreover, important geothermal exploration and drilling are now taking place in Chile, El Salvador, and Turkey. There is a growing interest in this natural source of energy, and many more countries are expected to take up large-scale exploration work in the near future.

A substantial amount of important scientific work has been devoted to both basic and applied aspects of geothermology. For a broad discussion, review of current theories, and further references, the reader is referred to the excellent paper by WHITE (1968), on the Steamboat Thermal System in Nevada, U.S.A.

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The papers by BODVARSSON (1961a), MCNITT (1965) and ELDER (1965) can be mentioned as further sources. The principles of the more practically oriented exploration work have received somewhat less attention in the literature. In particular, the problems involved in the evaluation of the potential of geothermal prospects and in the planning of exploratory work have apparently not been discussed on a broad basis. Nevertheless, since a number of geothermal areas in various parts of the world are being considered for exploitation, there is an increasing interest in these matters. This paper attempts to supplement the present literature by outlining some of the basic considerations which the writer finds to be involved in this type of work. The presentation which leans quite heavily on the writer's own experience in this field is a review of results obtained both in Iceland and other parts of the world. A brief description of the technique of geothermal exploration in Iceland has been given elsewhere (BODVARSSON, 1950).

HEAT EXTRACTION AND THE GEOTHERMAL RESERVOIR

In principle, the extraction of heat from subsurface formations for commercial purposes is a simple process. To clarify a few relevant concepts the elementary aspects of this process will be discussed briefly.

Large volumes of rock at high temperatures are known to exist below all major thermal areas. Almost any type of rock, igneous, sedimentary or metamorphic, may be involved. The cause of the elevated temperatures is not a matter of major practical concern and is still to be regarded as a partially unresolved problem. Although there can be little doubt that some types of magmatic intrusions in the upper crust constitute the ultimate heat sources of all high-temperature thermal activity, little is known about the form of the intrusions and the mode of heat transfer to the circulating water. Temperatures above 200 °C are usually recorded below high-temperature thermal areas at depths of only a few hundred meters, and higher temperatures are generally encountered at greater depths. When the permeability due to fractures or pores is sufficient, water can circulate through the hot rock, extract and convect some of its heat content, and return to the surface through springs or boreholes as thermal water or natural steam. Phase changes may occur within the reservoir or in the surface outlets depending on temperature and pressure conditions. Some reservoirs appear to contain mainly a gas phase. The water, which is the heat carrying medium in thermal areas, may be of meteoric origin and come from surrounding colder regions, or it may partially be of connate origin. The density of water decreases rapidly with the temperature, mainly above 200 °C; and therefore high-temperature thermal areas are, as a rule, under rather strong thermoartesian pressure resulting from the weight of the surrounding bodies of cold water. The extraction process is in many cases driven by the pressure of the encroaching cold water. Hot formations, where any form of heat extraction by flowing water is possible, constitute the geothermal reservoirs.

The transmission of heat from the reservoir rock to the flowing water depends heavily on the geometry of the permeability. The heat extraction can be efficient in sediments, where the water flows between small grains and where there is a great rock/water contact area. The efficiency can be relatively poor in igneous rock with only a few scattered permeable fractures. Elsewhere, BODVARSSON (1962) discusses quantitative aspects of the extraction process on the basis of simple models.

Two rather important facts have been revealed by geothermal drilling in Iceland, where a greater number of thermal areas have been explored by drilling than in any other part of the world.

First, the temperature of the reservoir rock, when unaffected by vapor pressure effects, is rather uniform in the individual areas. The permeability of the reservoir rock appears to be sufficient to sustain convective currents which lead to a large-scale temperature equalization within the reservoirs. This observation has led to the concept of the base temperature of a thermal area, which simply is the highest temperature observed in the thermally uniform part of a geothermal reservoir. A wide range of base temperatures has been observed. Hot water areas have base temperatures below 100 °C, whereas in some high-temperature thermal areas temperatures of 250°–360 °C have been observed. In the following, a thermal area which has a base temperature higher than 150 °C will be denoted as a high-temperature area.

Second, almost all thermal water in Iceland is under a rather strong artesian pressure, even at a shallow depth. This is significant because artesian cold water is practically unknown in Iceland. There is little doubt that the artesian pressure is of convective origin and is being maintained by a relatively low permeability in surface layers. BODVARSSON (1961b) has pointed out that some minerals, mainly silica and calcite, are dissolved at depth by the convecting thermal water and precipitated in surface layers because of changes in pressure and temperature. The thermal areas have thus a tendency to seal their surface outlets. "Old" thermal areas may not show any surface display.

The concepts introduced above can now be illustrated (Fig.1) with the help of the sketch of a simple hypothetical geothermal reservoir composed of layered igneous rock such as flood basalts. The pile of basaltic lava rests on a low permeability basement several kilometers below the surface. We assume that intrusions such as dikes, sills, and stocks, which have been emplaced in the basement, constitute the heat sources from which heat is being transported upward into the flood basalts by conduction and possibly also by fluid convection. In general, flood basalts series which are composed of a large number of individual lava flows have a large lateral permeability. The top and the bottom of each individual flow is usually scoraceous and porous, and the contacts between the lavas can therefore

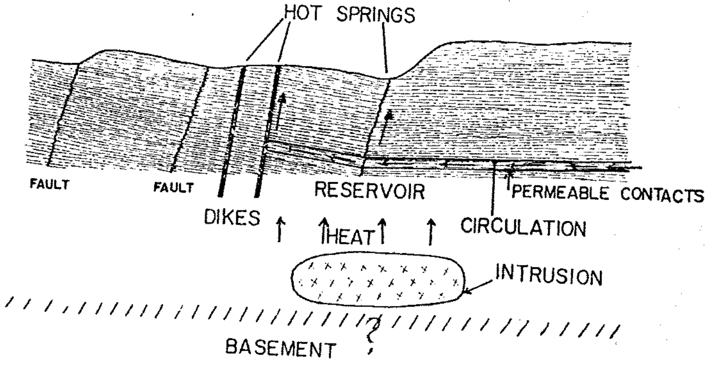

Fig.1. Geothermal reservoir in flood basalts.

be highly permeable to fluids. Moreover, vertical permeability is usually furnished by dikes and, to a lesser degree, by faults.

There are other types of geothermal reservoirs. The well-known geothermal reservoirs in Tuscany, Italy, appear to be at least partially composed of limestones with horizontally distributed solution openings. Moreover, the reservoirs in New Zealand are formed of sediments partially of volcanic origin. In general, geothermal reservoirs tend to have a rather complex geology. Examples of well-established base temperatures in high-temperature areas are: (*1*) Tuscany, Italy: 250 °C; (*2*) Iceland (several areas): 230°–300 °C; (*3*) Imperial Valley, California: 350 °C; (*4*) Mexicali, Baja California, Mexico: 350 °C; and (*5*) New Zealand (several areas): 255°–295 °C.

Very little is known about the total volumes of the reservoirs in these areas. However, the total volume of hot rock in the uppermost crust must amount to several hundred, if not several thousand, cubic kilometers. This figure is of major importance for the estimating of the total energy of a geothermal area. On the other hand, the power of an area, that is, the maximum rate at which the energy can be extracted depends on the maximum amount of reservoir fluid which can be drawn out of the reservoir. The fraction of the total heat content which economically can be "washed out" of a reservoir is referred to as the recovery factor. For further information on the concepts involved, see the paper by BODVARSSON (1966).

IMPORTANT CHARACTERISTICS OF GEOTHERMAL RESERVOIRS FOR LARGE-SCALE POWER PRODUCTION

At present, geothermal energy is mainly being exploited for the generation of electric power. With the exception of Iceland, the uses in the field of space and industrial heating are still of very little importance. In order to provide a basis for the evaluation of geothermal prospects, the main field conditions which in the view of the writer characterize high-power geothermal reservoirs will be outlined below.

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Reservoir temperature

The temperature within the reservoir, the base temperature, is the most important physical characteristic of a geothermal prospect. The physical and chemical processes within the reservoir depend critically on this quantity, and the technique of heat extraction has to be selected with regard to the temperature conditions.

In general, base temperatures above 200 °C will be necessary in order to sustain a power generation of the order of 100 MW or more. Temperatures in the range 200°–300 °C appear to be particularly favourable. The high temperatures present mainly two advantages. First, in the case of fluid-phase reservoirs, the vapor pressure is then sufficient to provide a steady production of steam by free flashing within boreholes. Second, the generating cycle efficiency is adequate But temperatures well above 300 °C may be less desirable because of their influence on the chemistry of the reservoir fluid. The solubility of many minerals increases rapidly with the temperature, and very high temperatures can therefore lead to complications because of the precipitation of chemicals in the higher parts of the reservoir and in wells.

Power generation is technically feasible at very low temperatures. Even thermal water at temperatures below 100 °C can easily be flashed at subatmospheric pressures and used to operate low-pressure turbines. But the thermal efficiency of the generating cycle decreases with decreasing temperature, and the specific throughflow of thermal water and cooling water increases substantially. The capital costs per unit power increase and power plants operating at low base temperatures are therefore economical only at very favourable conditions. A further difficulty at low base temperatures is the low vapor pressure of the reservoir water which often is insufficient to sustain a reliable steam production based on the technique of free flashing in wells. The production tends to be unreliable, and the wells may produce only intermittently. This difficulty mainly affects the temperature range 150°–200 °C depending on ground water conditions. At base temperatures below 150 °C the difficulties can in many cases be overcome by pumping the thermal water out of the wells. However, this technique requires the installation and operation of deepwell pumps which again increase overall costs. Moreover, the unit capacity of the pumps is limited by the well diameter resulting in a relatively large number of wells. Experience indicates that deep-well pumps can be operated reliably at or below 150 °C, but as yet it is not known whether this technique can be applied successfully at much higher temperatures. It is of importance to point out that since no flashing occurs in the hole, pumping tends to reduce the formation of scale within boreholes.

Reservoir volume

The overall efficiency of the conversion of geothermal energy to electric energy is very low (see BODVARSSON, 1962). In most cases only a small fraction of the reservoir heat, perhaps a few percent, can be recovered by boreholes. Moreover, the generating cycle efficiency is of the order of 10% at most; and, consequently, less than one percent of the reservoir heat may be converted to electric energy. A simple calculation shows that the effective energy content of a cubic kilometer of reservoir rock is of the order of 10^9 kWh of electric energy. As a consequence, the volume of geothermal reservoirs for large-scale power generation has to be of the order of hundreds of cubic km.

In general, extensive surface display of thermal activity, covering many square kilometers, will be indicative of a large reservoir volume. The reverse is not necessarily true. An insignificant surface display does not have to imply a small reservoir. Large reservoirs may show no surface display.

Reservoir permeability

The reservoir rock must have an adequate and suitably distributed permeability. Highly permeable clastic sediments are ideal as their heat content can be "washed out" in an efficient way. In the case of such rock, the recovery factor can approach unity.

But most of the known geothermal reservoirs are composed of igneous rock or limestone. These formations are permeable through fractures, tubes and other openings at the contacts of individual lava flows, and through solution openings. The distribution of the channels may be highly non-uniform, and this has an adverse effect on the ultimate heat recovery.

The relation between the permeability and the rock/water contact area has an important bearing on the phase of the fluid produced by boreholes. A reservoir with a large permeability combined with a relatively small contact area will produce water which may flash in the boreholes. On the other hand, a reservoir with a small permeability and a relatively large contact area may flash the water entirely within the reservoir and produce superheated steam.

Reservoir water

The principal geothermal heat carrier, water, must be available in adequate quantities. The regional meteorological and hydrological conditions are therefore of importance.

Main ground water level

The fluid flowing up through boreholes has to overcome both the static head due to the depth to the main ground water level within the reservoir plus some frictional resistance. The total head is of considerable practical importance in boreholes which are to produce by natural forces alone, namely by free flashing. Production cannot be initiated if the total head to be overcome is too great. The main ground water level must, therefore, not be too deep. Again, these problems can in some cases be solved by pumping the water out of the boreholes.

Chemical impurities

Loss of temperature and pressure of the reservoir fluid will in general precipitate some of the chemicals dissolved in the water, mainly silica and calcite. A high concentration of these impurities is undesirable since it leads to the deposition of solids in boreholes and equipment. Corrosion can also be of importance. At moderate base temperatures, the problems of deposition and scaling can often be solved by pumping the water out of the boreholes.

Drillability

The reservoir rock must be drillable at a reasonable cost, especially in the case of deep reservoirs. The question arises as to the maximum depth from which geothermal energy can be produced. In reservoirs now under exploitation, substantial production has been obtained from depths less than 1,000 m. Geological and economical conditions will vary greatly, and it is difficult to give a definite limit. However, it appears that production depths as large as 2,000 m will not be prohibitive if conditions are reasonably favorable.

Hidden reservoirs

As already stressed by BODVARSSON (1961b), thermal areas, and in particular areas characterized by waters with relatively high contents of silica and calcite, may have the property of gradually sealing off surface outlets. Thermal waters tend to dissolve silica and calcite at depth but precipitate these materials in surface layers because of loss of temperature and pressure. The water tends to open channels at depth but closes channels in near-surface layers. The sealing may possibly be quite rapid, and the zone of deposition may be of the order of 500 m thick, but this figure is largely a guess. Some thermal areas of a relatively advanced "age" may have closed all surface outlets, although there is a large active reservoir at depth. There may only be a mild heat flow anomaly above the reservoir. Moreover, rapid weathering may contribute to a quick eradication of the surface features. Large-scale exploration for hidden high-temperature reservoirs can therefore be recommended in regions of volcanism, provided there is a sufficient market for geothermal energy.

GLOBAL DISTRIBUTION OF GEOTHERMAL PROSPECTS AND PRODUCTION COST

High-temperature geothermal resources may be present in any belt of active volcanism. Therefore, the entire circum-Pacific belt, the Lesser Antilles, Iceland, the Italian–Aegian belt, and the African Rift zone are areas of geothermal interest. There appears to be an interrelation between the chemistry of the lava erupted in these zones and the frequency of areas of geothermal activity. Most, if not all, high-temperature areas show a close connection with eruptive centra that have produced silicic lava or tephra in great amount. This is perhaps most conspicuous in Iceland where the volcanism is predominantly mafic, only about 5% of the lava erupted is of the silicic type. However, three or four of the largest high-temperature areas in Iceland are located at centra which have had a very recent history of silicic eruptions.

Experience in Italy, Iceland, California, Mexico, and New Zealand shows that under reasonably favorable conditions geothermal heat can be produced at very low cost. The production cost of natural steam delivered to power plants has in some of these areas been of the order of 0.25 $/metric ton, which is about $\frac{1}{5}$ of the lowest possible cost of steam derived from fuel. Of course, due to low temperature and pressure, the exergy* (capacity of the unit mass of the steam to produce mechanical work) of natural steam is only about $\frac{1}{2}$ of the exergy of steam from fuel. Therefore, the most economical uses for natural steam are in the chemical industry where there is a need for power and heat. The paper and pulp industry is a very good example.

PROSPECTING FOR GEOTHERMAL RESOURCES

The methods of prospecting for geothermal resources fall roughly into two main classes: (*1*) the direct methods which probe the subsurface temperature field; and (*2*) the indirect methods which are mainly being applied to structural problems (see BODVARSSON, 1961a). The first class includes the thermal, electrical and chemical methods. Moreover, the microearthquake technique which is still in its developing phase can possibly also be classified as a direct method. The second class includes the more common methods such as the seismic, gravity and magnetic methods. Their application to geothermal prospecting is substantially along similar lines as in the field of hydrology.

Thermal methods

The base temperature constitutes the most important physical characteristic of a geothermal prospect. The thermal methods such as temperature probing in boreholes and heat flow mapping at the surface are consequently of primary importance. The measurement of temperatures in deep boreholes is the only reliable method of providing information on the base temperature of a given geothermal prospect. In general, it is therefore necessary to resort to deep exploration drilling before reliable final results can be obtained. The depth of such wells has to be of the order of 1,000–1,500 m. Data on geology and permeabilities are also furnished by the exploratory wells. Since the surface above geothermal reservoirs is usually characterized by high heat flows, the mapping of the surface heat flow is in many instances helpful to outline the main contours of a geothermal

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* The exergy concept is now used in modern literature on thermodynamics.

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Electrical methods

The application of electrical methods in geothermal prospecting is based on the fact that the electrical conductivity of rocks increases rapidly with increasing temperatures. More over,the conductivity of geothermal areas is also enhanced by the usually high degree of metamorphism in these areas. The thermal waters are highly conductive due to a heavy load of dissolved solids. The electrical methods have, therefore, the capacity of directly probing the subsurface temperature conditions although there is always a great ambiguity involved in the interpretation of electrical data. There is no unique relation between the temperature and the conductivity.

Very little has been published about the conductivity distribution in geothermal areas. According to results which have been obtained by rather shallow Wenner-type resistivity probing in Iceland, and which appear to be substantiated by incomplete data obtained elsewhere, the conductivity of the uppermost sections of high-temperature thermal areas can be of the order of 0.1–1.0 mho/m. These values exceed the conductivity of rocks at ordinary conditions by factors of the order of 10^3–10^4. A downward extrapolation of these values is somewhat uncertain. The conductivity at depth may increase further due to higher temperatures. On the other hand, it is conceivable that there is an absolute conductivity maximum at a very shallow depth due to the acidic or low pH condition in near-surface layers. This remains an open question which has not yet been completely resolved. In any case, there are good reasons to believe that the conductivity may decrease at depths of several kilometers where the water content of the rock is affected by lower porosities.

The principal drawback of the common electrical resistivity methods is the relatively shallow penetration. Deeper probing requires special equipment, which is still in its developing phase and is not commercially available.

Chemical methods

The equilibrium of many chemical processes is highly temperature dependent. There is little doubt that the chemical composition of thermal waters and thermal gases is dependent on reaction temperatures in the reservoir environment. The chemical data on the waters and gases, therefore, may provide clues on subsurface temperatures.

The simplest case of chemical thermometry is the method based on the SiO_2 content of spring water which has been developed in Iceland (BODVARSSON and PALMASON, 1961). The amount of dissolved SiO_2 depends on the reaction temperature, and equilibrium values are reached very slowly. Therefore, spring water which has been cooled on the passage to the surface may still retain the

SiO_2 concentration acquired at higher temperatures within the reservoir rock below. It has been possible to use this method with success in Iceland in order to obtain data on base temperatures. The gases intermixed with hot spring water and natural steam may also furnish information on the subsurface temperature field. Mainly the H_2 content of natural steam is a temperature indicator.

Microearthquakes

It has been well known for a long time that high-temperature areas are seismically very active. This has been substantiated by the recent microearthquake studies in Iceland by WARD et al. (1968). The monitoring of microearthquakes may therefore prove to be a technique of practical importance for the purpose of locating regions of high thermal activity.

CONCLUSIONS

In view of present experience it is possible to outline a number of characteristic features of geothermal reservoirs which are capable of sustaining power generation in the 100 MW range. The base temperature has to be quite high, or preferably 200°–300 °C. The reservoir volume has to be at least of the order of several hundred cubic kilometers. The permeability of the reservoir rock must be adequate and ground water must be available in sufficient quantities. The depth to the ground water table should not be too great and the water should not contain dissolved solids in great quantities. The puming of geothermal boreholes is often advisable in order to improve production. Thermal, electrical, chemical and microearthquake methods of exploration can furnish data on the subsurface thermal processes and are therefore of importance in geothermal prospecting.

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